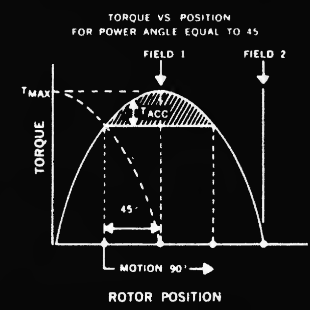
STEP-SERVO MOTORS



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DEFINITION OF TERMS

1. **Maximum Response.** The maximum pulse rate which can be applied to a step-servo in a random manner (CW and CCW) that will result in synchronized steps.
2. **Slew.** The high speed area of performance where the step-servo is following commands (either CW or CCW) unidirectionally in synchronism. The unit can not stop, start or reverse on a given pulse in this area. To reach the slew area the pulse rate must be reduced below the maximum response point and then increased to the slew area. If the step-servo is forced out of slew it will stall and not rotate until the pulse rate is reduced below the maximum response point.
3. **Power Angle.** The angle of lag of the rotor to the axis of the magnetic field under load.
4. **Maximum Running Torque.** The maximum torque that can be delivered at the shaft when the motor windings are sequentially energized from one "on" position to the next (dynamic mode). This occurs at pulse rates in the order of 5 pps.
5. **Stall Torque.** The maximum torque a unit can deliver or hold when the motor windings are energized at zero pulse rate (static mode). This torque value occurs at 90° displacement from the no load position. Stall torque *cannot* be delivered under dynamic conditions.

GENERAL

A step-servo motor is a device which, when energized by DC voltages in a programmed manner, indexes in given angular increments. Its angular displacement is either CW or CCW and is determined by the sequence in which the windings are pulsed.

There are basically two types of step-servo motors. The first works on the reaction between an electromagnetic field and a permanent magnet. This type is classified as a *Permanent Magnet Step-Servo* (PM). The second type works on the solenoid action and is called a *Variable Reluctance Step-Servo* (VR). This unit works on the reaction between an electromagnetic field and soft iron rotor.

Step-Servo motors can be likened to a series of solenoid coils arranged in a circle which, when sequentially pulsed, will react with a soft iron core as in the VR motor or a permanent magnet as in the PM motor and move Ψ degrees. (See Fig. 1 Below).

The torque or reaction of the moving element is not a constant for each incremental motion. The torque, although not constant from point 1 to point 2 is however repeated when moving from point 2 to point 3.

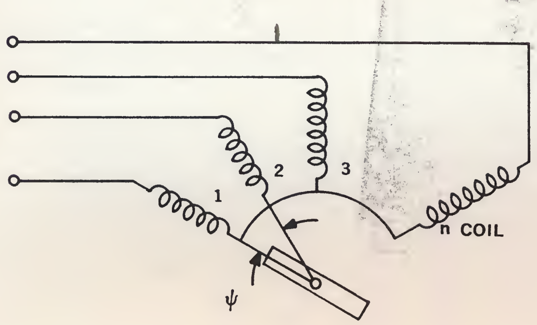


Figure 1

The stepping angle "Ψ" is determined by design but can not be greater than $\frac{2}{3}\pi$ and still have directional characteristics and uniform motion. It is possible, size allowing, to make the steps any value $\frac{2\pi}{n}$ where $n \geqq 3$.

Using large numbers of coils has certain disadvantages, however, since a small portion of the available copper is used, therefore requiring a larger motor package to obtain the same delivered torque. There are, however, several methods for reducing the stepping angle without this drawback. These will be explained later.

Switching from one winding to another in a sequential manner 1, 2, 3, . . . n, 1, 2, . . . results in a non-linear motion of $\frac{2\pi}{n}$ radians per switch. The shaft will rotate at an average speed in accordance with the following equation:

$$N_{av} = \frac{60\,(PPS)}{n}$$

PPS = Pulses/sec.
n = Phases
N_{av} = Speed in RPM

The average speed will be in synchronism with the rate of pulsing. The resultant angular motion will be x radians/switch. This is a conversion from digital data to analog position. This exact relationship between pulses and angular motion is the most important characteristic of Step-Servo Motors.

High speed switching by means of solid state devices has accelerated the growth of Step-Servo Motors. D.C. power can now be converted directly into precise rotational motion in synchronism with input intelligence. This is schematically represented below. Each pulse results in the output shaft moving Ψ degrees either CW or CCW.

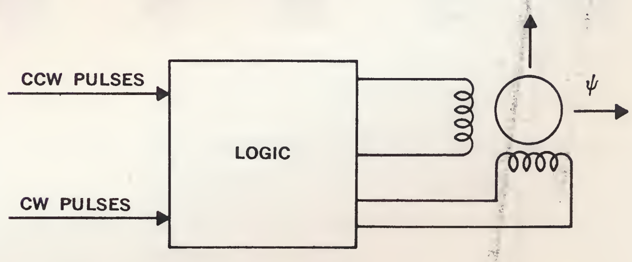


Figure 2

Step-Servo motors have many advantages over linear devices. They offer:

1. Fast response (Response time as low as 1 millisecond)
2. Insensitivity to linear vibration and shock
3. Long life (Up to one billion cycles)
4. Accurate motion with magnetic detents
5. Insensitivity to voltage and pulse amplitude variations

The versatility of this motor is also highly significant. It may be used as a:

1. Variable frequency motor (eliminate gear changing)
2. Brushless DC motor
3. Open loop servo to eliminate feedback circuits
4. Incremental output motor
5. Digitally driven motor
6. Synchronous motor
7. Pulse Counter (integrator)

The step-servo when pulsed to its maximum capabilities is considered to be within its synchronous state.

The step-servo has an additional characteristic beyond its synchronous or reversible state, which is its high speed slewing capability. In this mode unidirectional synchronism is possible. The rotor will follow the pulsating field the same as in a synchronous motor. This property is used to extend the range of operation of the step-servo to areas where high rotational speed rather than reversible synchronism is required. When in slew the unit does not lose synchronism (unidirectionally) but cannot stop, start, or reverse on a given command. As an area is approached where the unit is required to stop precisely, the pulse rate must be reduced within the response range.

MANNER OF OPERATION

Let us examine what occurs with the step-servo motor under dynamic conditions at one pps and no load. The rotor indexes from position 1 to position 2 as shown below:

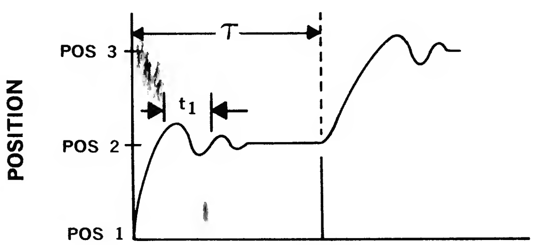


Figure 3

The speed with which the unit moves is determined by

$$T_{unit} = I\alpha \quad \text{where } T = T_{(maximum)} \sin \Psi$$
$$I = \text{Total Inertia}$$
$$\alpha = \text{Angular Acceleration}$$

This results in an oscillating type motion. These oscillations are damped by the permanent magnet in the PM motor or by eddy currents in the VR motor. As the frequency of pulsing is increased the period τ becomes shorter. When the period of the pulses is in the order of the oscillatory period t_1 the unit has reached its maximum pulse rate as shown above.

A further increase in the pulse rate, unidirectionally, results in slew which is shown below:

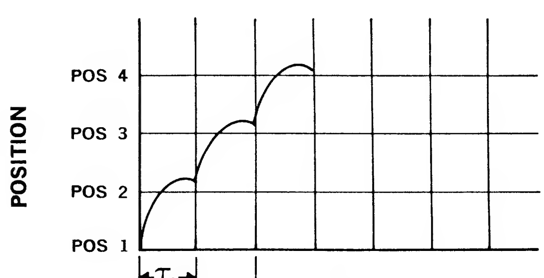
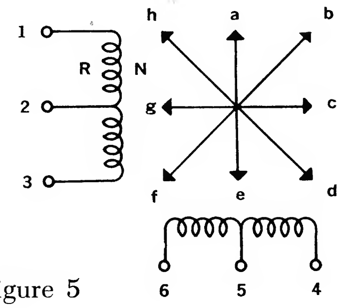


Figure 4

Reducing the step-servo's air gap tends to increase the stall torque but also results in a reduction of the maximum pulse rate. This occurs because the rotor becomes overdamped. Friction loads obviously have the same effect. Inertia loads increase the oscillatory period thereby reducing the maximum pulse rate, as well as creating resonant conditions at various frequencies.

STEP-SERVO EXCITATION

Consider a permanent magnet, 2-pole step-servo motor. These are primarily 90°/step, 2-phase types. Angles of 45°, 180°, 360°, etc., can also be obtained however by the manipulation of the logic and the introduction of pulse multipliers. As an example, a single pulse which would result in 90° motion could be multiplied by 4 and would result in a 360° motion. The motor in either case is still a 90° step-servo. Using the following schematic, various techniques for excitation are illustrated.



N = Turns
R = Resistance
V_{DC} = Voltage

Figure 5

	WINDINGS TO WHICH VOLTAGE IS APPLIED	POSITION	MOTION
Excitation-Technique A	V_{1-2} and V_{4-5}	b	—
	V_{3-2} and V_{4-5}	d	90° CW
Commutation of B+ only	V_{3-2} and V_{6-5}	f	90° CW
	V_{1-2} and V_{6-5}	h	90° CW
Excitation-Technique B	V_{1-3}	a	—
	V_{4-6}	c	90° CW
Commutation of B+ and B—	V_{3-1}	e	90° CW
	V_{6-4}	g	90° CW
Excitation-Technique C	V_{1-2}	a	—
	V_{1-2} and V_{4-5}	b	45° CW
Energizing one winding then 2 windings in parallel and then 1 winding, etc.	V_{4-5}	c	45° CW
	V_{4-5} and V_{3-2}	d	45° CW
	V_{3-2}	e	45° CW
	$V_{(1-4)}$ (3,6 CONNECTED)	h	—
Excitation-Technique D	$V_{(1-6)}$ (3,4 CONNECTED)	b	90° CW
Windings in series	$V_{(4-1)}$ (3,6 CONNECTED)	d	90° CW
	$V_{(6-1)}$ (3,4 CONNECTED)	f	90° CW

There are many sequences which electronically will vary the angle moved by the rotor. These sequences may appear to be equivalent but in reality their efficiency may vary by a factor of 4 to 1.

EFFICIENCY OF mmf GENERATION

Let us examine a 2-phase motor, schematically shown in Figure 5, and assume we excite it first by commutating B+ only (Technique A) and then by commutating B+ and B− (Technique B). We can compare the mmf developed as well as the power necessary to produce this mmf and from this calculate the relative efficiency.

Excitation Technique A Two half windings in parallel	*Excitation Technique B* One winding alternately
$I=\frac{V}{R}$	$I=\frac{V}{2R}$
amp turns$=N\frac{V}{R}$	$\Sigma NI=(2N)\frac{V}{2R}$
Total amp turns$=(\vec{NI})+(\vec{NI})$	Total amp turns$=\frac{NV}{R}$
(a) $\boxed{(NI)_T=1.4\frac{NV}{R}}$	(a) $\boxed{(NI)_T=\frac{NV}{R}}$
Power$=$ VI	Power$=$VI
(b) $\boxed{P_T=\frac{2V^2}{R}}$	(b) $\boxed{P_T=\frac{V^2}{2R}}$
Factor$=\frac{NI_T}{P_T}=\frac{1.4\frac{NV}{R}}{2\frac{V^2}{R}}$	Factor $\frac{(NI)_T}{P_T}=\frac{\frac{NV}{R}}{\frac{V^2}{R}}$
(c) $\boxed{\text{Factor}=0.7\frac{N}{V}}$	(c) $\boxed{\text{Factor}=\frac{2N}{V}}$

$$\%\ \text{IMPROVEMENT}=\frac{2\left(\frac{N}{V}\right)}{0.7\left(\frac{N}{V}\right)}\times 100$$

IMPROVEMENT=286%

This shows that it is possible to produce the same mmf, therefore the same output characteristics, with approximately one third the power. A reduction of input power allows the step-servo to run cooler thus increasing its life. The maximum utilization of windings and power occurs if both windings are excited in series. A comparison of excitation D and A is as follows:

Excitation Technique A	*Excitation Technique D*
As Derived	$I=\frac{V}{4R}$
	$\Sigma NI=\left(2N\frac{\vec{V}}{4R}\right)+\left(2N\frac{\vec{V}}{4R}\right)$
(a) $NI_T=1.4\frac{NV}{R}$	(a) $NI_T=0.7\frac{NV}{R}$
(b) $P_T=\frac{2V^2}{R}$	(b) $P_T=\frac{V^2}{4R}$
(c) Factor$=0.7\frac{N}{V}$	(c) Factor$=2.8\frac{N}{V}$

$$\%\ \text{IMPROVEMENT}=\frac{2.8\left(\frac{N}{V}\right)}{0.7\left(\frac{N}{V}\right)}\times 100$$

IMPROVEMENT=400%

The optimum excitation D is rather complicated. The choice of logic is dictated by cost, size of logic, etc. It is not always practical to choose a logic which gives the step-servo maximum efficiency. When power available, life, and size are critical the choice of logic becomes paramount. Generally, the power loss in switching is low, compared to the motor's I^2R losses. It is therefore wise to use a less efficient drive if it will improve the step-servo's efficiency.

PM STEP-SERVO MOTORS
(Dynamic Characteristics)

What occurs from the time of excitation will now be analyzed. For the purpose of analysis, we will assume the voltages appear as follows:

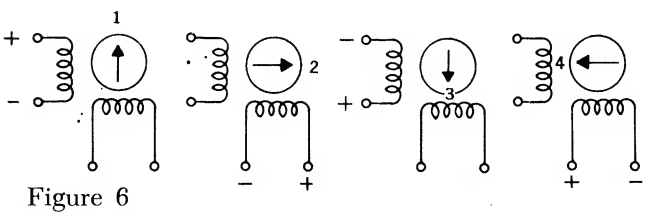


Figure 6

When the first winding is excited the permanent magnet rotor aligns itself with the field. The torque delivered at this point is zero. As a torque load is applied, the rotor will displace θ degrees and a torque is developed as follows:

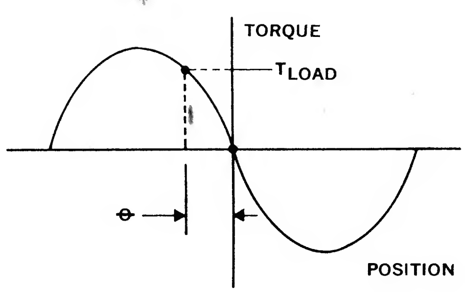


Figure 7

Maximum torque is developed at 90°. This is called the stall torque. If we load the unit to an angle of 90° as shown below

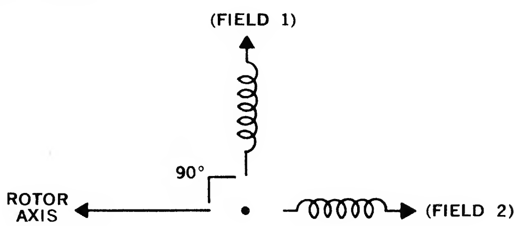


Figure 8

and excite winding II, a field 180° from the rotor field is created. At this point zero torque is developed.

$$T = T \text{ maximum} \sin 180^\circ$$

$$T = O$$

It is obvious that stall torque is not usable if sequential pulsing is applied and rotation is required.

The maximum torque, in a dynamic sense, which can be developed occurs when the rotor's angular lag (Power Angle) does not exceed 45°. This can be seen by the following:

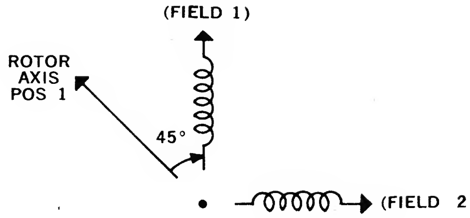


Figure 9

Torque when winding I is excited

$$T = T \text{ maximum} \sin 45^\circ$$

$$T = .707 \text{ T maximum}$$

At the instant winding II is excited and winding I is opened, the rotor power angle is 135° and the torque is:

$$T = T \text{ maximum} \sin 135^\circ$$

$$T = .707 \text{ T maximum}$$

As the rotor starts to move it passes through 90° where maximum torque occurs. The condition where the power angle is equal to 45° is illustrated below:

TORQUE VS. POSITION FOR POWER ANGLE EQUAL TO 45°

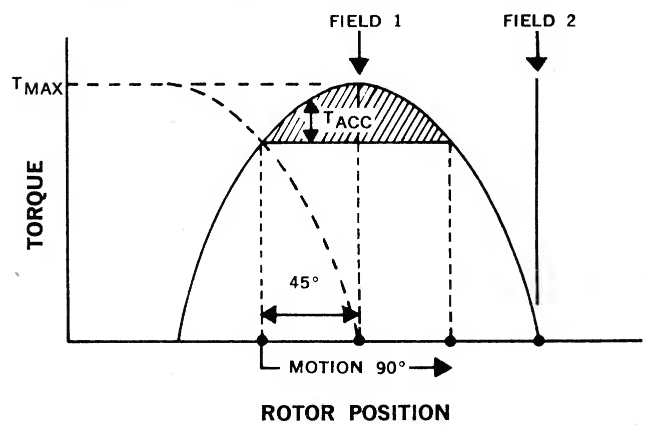


Figure 10

In practice this power angle should not exceed ≅ 30°. This is illustrated below:

TORQUE VS. POSITION FOR POWER ANGLE EQUAL TO 30°

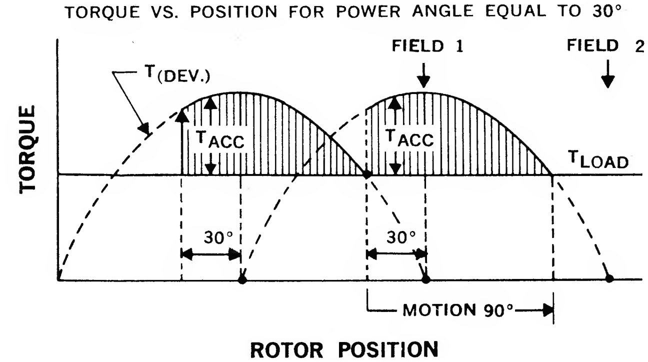


Figure 11

The accelerating torque is the difference between T developed and T load [$T_{accelerating} = (T_{developed} - T_{load})$]. In the case of a 45° power angle, the load torque equals the developed torque at switching and no accelerating torque is developed; this produces instability. It is necessary to limit the power angle to less than 45°.

The acceleration of the rotor is caused by $T_{accelerating}$. From the curves drawn it is seen that this accelerating torque is represented by the distance between the load line and the developed torque. The differential equation of motion is:

$$I \frac{d^2\theta}{dt} + K_d \frac{d\theta}{dt} + K_S \sin \theta = T_L$$

I = Inertia
K_d = Damping Factor
θ = Angle of Motion
K_S = Maximum Torque Developed
T_L = Load Torque

Angle θ varies through a large range (0-135°) which eliminates any simplifying assumptions. The solution of this equation leads to an elliptic integral. Rather than perform laborious mechanical integration to obtain an analytic solution, the resultant motion of a step-servo rotor was observed. This motion was analyzed by monitoring the current into the step-servo as the unit was pulsed in 90° steps. Oscillations of the rotor induced current variations which were viewed on a scope. The motion, as expected, is of a damped harmonic nature. Inertia loads, friction loads, etc., were added and the motion monitored. Inertia loads increased the period which under some conditions cause resonance points. If a resonant condition is generated, additional damping is required. Friction loads increased the damping and reduced the maximum pulse rate.

VR STEP-SERVO MOTORS (Dynamic Characteristics)

Variable reluctance step-servo motors are gaining wide acceptance because of the ease with which small angular steps are obtained and because of their ability to run at high pulse rates. (up to 1200 pps bi-directionally). The operation of a VR motor is shown schematically below:

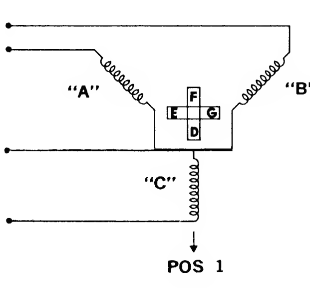


Figure 12

When winding "C" is energized with D.C. the rotor aligns itself with the resultant pole "D". When winding "B" is energized the closest pole "G" moves 30° into alignment. When winding "A" is energized, pole "F", 30° away, moves into alignment, etc. Under these conditions stepping angles of 30° are obtained. The polarity of the applied voltage is immaterial since the rotor moves to a minimum reluctance position. This characteristic provides flexibility in generating various stepping angles. Two ways of obtaining 15° steps are illustrated below:

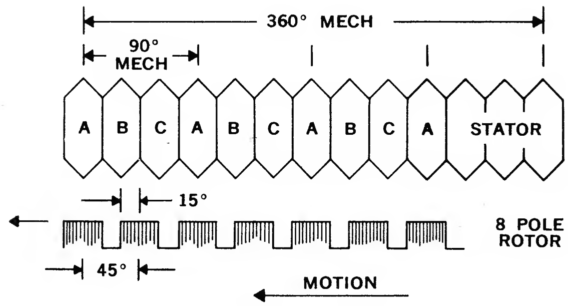


Figure 13

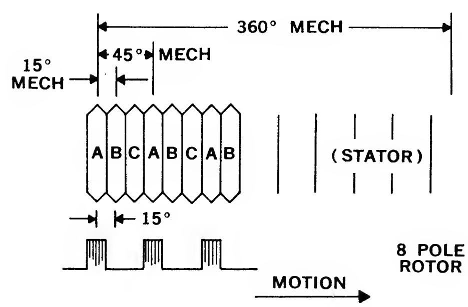


Figure 14

The relation, in an electric machine, between mechanical degrees and electrical degrees is, in effect, magnetic gearing. Using an 8 pole rotor and 8 pole stator results in the same angular 15° step as an 8 pole rotor and a 4 pole stator, but with reversed direction. The choice between the above two is dictated by the size, ease of manufacture and performance. For small machines, (size 23 or under) method I is recommended since fewer poles are required. This results in the use of fewer slots and coils. The dynamic torque characteristics (below) of both PM and VR step-servos are similar. The primary differences are in the mechanical angles and the maximum torque load capability.

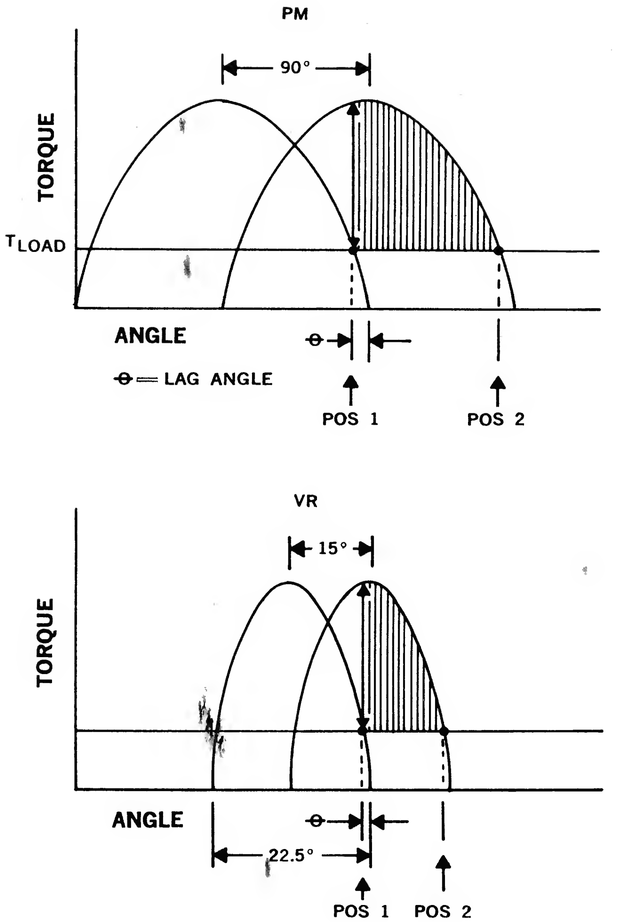


Figure 15

It has been shown that the maximum load torque for a 90° step-servo is:

$$T = .707T_{(maximum)}$$

For the VR previously discussed the following is applicable:

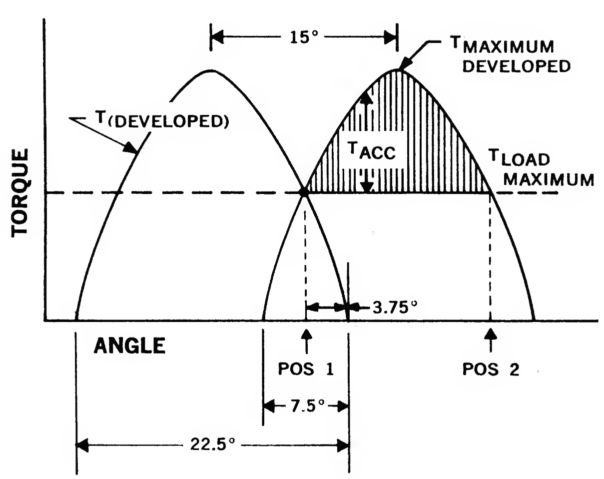


Figure 16

$$T_{(load\ maximum)} = T_{(maximum\ developed)} \sin \frac{3.75}{11.25}\left(\frac{\pi}{2}\right)$$

$$= T_{(maximum\ developed)} \sin 30°$$

$$T_{(load\ maximum)} = .500\ T_{(maximum\ developed)}$$

For the 15° step-servo described, the maximum load torque which can be applied is equal to one half the maximum developed torque.

PERFORMANCE CHARACTERISTICS

Test curves run on step-servo motors relate the average torque capacity to the pulse rate. In general three points known are:

1. Maximum Pulse Rate
2. Stall Torque
3. Running Torque

These points are shown below:

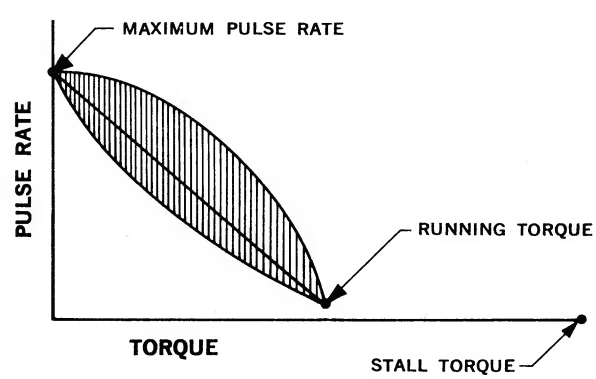


Figure 17

From published data it is possible to construct the approximate torque vs. pulse rate curve. These curves are limited on each end by maximum pulse rate and running torque. It is apparent that the stall torque value is useless in dynamic operation. As shown, the running torque for a 90° PM step-servo is approximately one half the stall torque. The addition of inertia, friction, etc., will change the shape of the curve as well as reduce the maximum pulse rate.

CONCLUSIONS

(1) The use of the correct step-servo is determined by load conditions and performance required.

A. *Permanent Magnet Step-Servos* should be used when:

1. Non-ambiguity is desired
2. Large stepping angles are desirable
3. Pulse rate is low (300 pps maximum bidirectionally)
4. Magnetic detenting is desired

The choice of the correct PM step-servo is determined by the load, pulse range and power available.

B. *Variable Reluctance Step-Servos* should be used when:

1. Pulse rate is high (1200 pps maximum bidirectionally)
2. Ambiguity of position is unimportant
3. Small angular output steps are desired (thereby eliminating or reducing gearing)
4. Magnetic detenting is not desired
5. Presence of magnets is not allowed

The choice of the correct VR step-servo is also predicated on the same factors as a PM step-servo.

(2) *Step-Servo Motors* should not be confused with induction or synchronous motors. Testing and evaluation of performance should be analysed in relation to the mode of operation. Parameters such as stall torque which are of great importance in synchronous and induction motors are not applicable to step-servo motors.

Step-servo motors and their accompanying logic circuitry comprise a basic step-servo system. The advantages of these systems are evident in the following statements:

1. Step-servo system *response is the fastest available* of any inductive device today (in the order of 1 millisecond).
2. *High resolution* accompanied by *high sweep rates* are possible.
3. Step-servo systems are *not affected in operation by varying environmental conditions* thus offering more reliable, more maintenance-free operation than with present AC servo systems.
4. *No hunting or oscillation* to contend with as in AC servo systems.
5. As straight digital devices, *the need for digital to analog voltage conversions is eliminated.*
6. When used as open loop servos, *they do away with costly feedback circuits.*
7. The electronics portion in customer systems has in instances *required only 25% of the space needed by AC servo circuits* with comparable reductions in weight also afforded.

IMC

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